Use of Signal and Ambient Noise Coherence to Optimize Sonar System Performance

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LONG-TERM GOALS

Acoustic transmission measurements from the 1996 ONR summer Shelfbreak PRIMER exercise [1] have shown that both acoustic signal and noise intensity levels exhibit fluctuations on the order of 20 dB, primarily due to the temporal variability of the local shallow water environment. During this on-going project, our first goal has been to relate the fluctuations in the signal and noise intensity levels, and their correlations to the relevant oceanographic features such as internal solitary waves and/or tides, shelf-break fronts, internal surface ducting, etc. Our analysis of the PRIMER data set has shown that there can be correlation between the signal and noise intensity fluctuations, and also between these fluctuations and the internal wave and tidal cycle fluctuations in the water column. Next, we plan to demonstrate that these correlations are significant in other important littoral regions. Our final goal is to develop practical methods of optimizing sonar system performance by exploiting these correlations.

OBJECTIVES

The objectives of this research are to 1) provide a quantitative relationship between the signal and noise intensity fluctuations; 2) relate the signal and noise intensity variations to important oceanographic processes such as internal solitary waves, internal tides, finestructure and mesoscale frontal features; 3) understand the signal, noise and oceanographic relationships in order to improve sonar system operations; and 4) develop techniques for real world war fighters which optimize the statistical gain associated with these relationships. This project follows closely with one of ONR's primary goals of transitioning basic research into real world usable navy products to enhance acoustic system performance.

APPROACH

Through a series of field experiments (PRIMER, ASIAX, etc.) supported by ONR it has been clearly demonstrated that littoral internal waves can significantly impact acoustic propagation. This project, initiated in January 2003, is aimed at addressing how to utilize information gleaned from these experiments to help optimize sonar system performance. Our initial work has focused on the ONR PRIMER data, and future work will include the analysis of SHAREM or ASIAX data collected in the East China Sea.

Our technical approach is to examine the signal and ambient noise intensity fluctuations as well as the oceanographic processes (i.e. internal solitary waves) and determine the appropriate correlations over time. To assist in this analysis we have begun to process these fluctuations using cross correlation, digital filtering and FFT (power spectrum and coherence) techniques. The oceanographic fluctuations, are expressed in an empirical orthogonal functional (EOF) representation of the water column temperature near the acoustic recievers. These analyses quantify relavent frequencies of the signal, noise and ocean fluctuations and help identify the dominant physical features. We also plan to use coherent output power spectrum calculations and a transfer function technique to determine when the signal and noise intensity variations are related and/or coherent and how one might exploit these relationships in a sonar system. For datasets such as the PRIMER experiment, in which data are measured with a vertical receiving array, we also plan to use vertical beamforming and/or modal decomposition so that the channel response can be selectively analyzed. The principle investigator, Mr. Philip Abbot is acting as technical director for this work, with most of the technical effort conducted at OASIS, Inc. by Dr. Charles Gedney and Mr. Christopher Emerson. Dr. Louis Goodman of the University of Massachusetts Dartmouth is a consultant on the project. The data were provided by Dr. Ching-Sang Chiu of the Naval Postgraduate School.

WORK COMPLETED

Internal waves can affect both the received signal as well as the background noise on which the received signal is superimposed. The approach of this project is to examine the nature of the statistics of the signal and noise fields, relate these to the oceanographic fluctuations and apply this information to developing techniques that improve sonar performance (increasing the probability of detection and/or reducing the probability of false alarms).

To accomplish this goal, it is essential to have a thorough understanding of both the physical oceanography and the acoustics of these phenomena and how war fighters could utilize this information. As an example, for a passive sonar system, the simple and most commonly used technique for detecting a target is the so-called "energy" detection method [2, 3]. In this method, a threshold value is set. If the received signal is above the threshold, detection of a target is said to occur; if the signal is below this value, no detection is made. If the probability density functions (PDF's) of the signal plus noise and the noise alone are known, then the probability of detection (PD) and the probability of false alarm (PFA) can be easily found for any given threshold level, by simply computing the area under each PDF above the threshold [3]. The so-called "receiver operator characteristic" or ROC curves give PD and PFA as the threshold is varied for fixed signal plus noise and noise PDF's (a fixed signal-to-noise ratio) [3]. Typically, these PDF's are assumed to be statistically independent and Gaussian. However, if coherent fluctuations are introduced into the signal and noise by the environment, then the respective PDF's will change and a new set of ROC curves will be needed. In general, the signal and noise variances will not be equal. The sonar operator may also be able to exploit the coherence in the fluctuations to reduce the variance in the signal plus noise PDF and increase the PD (when the threshold is set below the signal plus noise mean). To help with this task, some knowledge of the PDF's can be obtained by making background measurements of the fluctuating noise field. In addition, much is already known about the variations in the oceanography and how they affect acoustic propagation. Thus, a thrust of our work is in understanding how this in situ and a priori information may be used to improve sonar system performance.

Our studies this year have concentrated on the fluctuations in the signal and noise intensity fluctuations measured during the summer 1996 Shelfbreak PRIMER experiment and how they relate to the local oceanography. A summary of this work is presented in the next section.

RESULTS

Our initial effort has primarily focused on relating signal and noise intensity fluctuations to the internal wave field. To date we are principally concerned with what type of gains could be made from the correlation between the signal intensity level, the noise intensity level and the internal wave field temperature displacement from a single location. Figure 1a shows time series of the depth averaged (over 16 hydrophones spaced from 30 to 85 m deep) intensity levels: the top curve is the signal; the second curve is the noise. The third curve in this figure shows the depth averaged and 5 minute averaged cross correlation coefficient between the signal and noise; the bottom curve is the time series of the first mode internal wave signal from the PRIMER temperature-chain mooring. The signal, noise and internal wave show clear evidence of the internal semi-diurnal tide signal at a period of about 12 hrs. Note also that even after this depth average, both the signal and noise levels still have a variability of about 10 dB. The third curve in this figure shows that, over a period of 5 min, the depth averaged signal and noise levels have a significant cross correlation coefficient (0.1 to more than 0.5). This compares to a significance level of about 0.1 for signals of this type.

Figure 1b shows a contour plot of the 5 min cross correlation coefficient, r, between the signal and noise intensity levels versus depth and time. Remarkably, there is a wide variation (shown as the extreme graininess of this figure) in r between 0 and near 1. This indicates that both the signal and noise are undergoing, at times, the same effects of the environmental processes.

Spectra of the signal, P, noise, N, and first mode internal wave temperature induced variability are presented in figures 2a and 2b. Figure 2a has 4 degrees of freedom and resolves frequencies at the semidiurnal tidal frequency (1/12 cycles/hr). All three spectra in this figure show a peak near this frequency, although the received signal peak appears to be a bit displaced to a lower frequency. Since there are only 4 degrees of freedom and the spectral resolution is of order 1/48 cycle/hr, the small differences at the semidiurnal tide cannot be ascribed to any significance within the uncertainty of the analysis. In figure 2b we show the same three spectra calculated with 10 degrees of freedom. We trade off loosing the low frequency resolution and resolving the semidiurnal tide with better accuracy in the higher frequency range. Two very interesting features of figure 2b are: 1) the noise (in dB) has a much higher variance than the received signal over much of the frequency range and 2) the signal spectrum seems to have a very similar shape to that of the internal wave field. Note that the frequency range from 0.1 to 2 cycles/hr is the range of the so-called broad bandwidth internal waves. Internal solitary waves would affect the frequency range of order 1 cycle/hr and larger. Figure 3 shows the coherence between the signal and noise, labeled PN, shown in blue; between the internal wave induced temperature field and received signal, labeled TP, shown in green; and between the internal wave induced temperature field and noise, labeled TN, shown in red. The black dashed line is the significance level for 10 degrees of freedom. Clearly the received signal and noise have a large frequency range of coherence, while, in general, the noise appears to be more coherent with the internal waves than the signal with each having different frequency ranges where the increased coherence occurs. It is this type of information that may lead to improved sonar performance if it is properly taken into account.

Our future plans include similar investigations of the signal and noise levels measured in other datasets such as the ASIAX and SHAREM exercises conducted in the East China Sea. However, for these studies, new issues will arise such as the influence of the source and receiver positions, signal type (frequency, bandwidth, and pulse width), and the source and location of the ambient noise (shipping, sea surface, etc.), as well as the oceanography (sea surface conditions, internal waves and tides, fronts, surface ducting, etc.) and bottom conditions. These new influences will be investigated so that the final project conclusions will be more widely applicable.

IMPACT/APPLICATIONS

Clearly, variations in signal and noise levels directly affect the performance of sonar systems. By investigating these variations and how they are affected by the oceanography, we hope to develop methods that can be used to optimize sonar system performance. If the signal and noise level variations are related over some frequency bands, then information obtained in situ about the noise and oceanography may be helpful in this endeavor.

RELATED PROJECTS

The Capturing Uncertainty DRI, which is currently being sponsored by ONR code 32 (Ellen Livingston), is closely related to the work reported here. Under the Uncertainty DRI, the work has been to enhance the understanding of the uncertainty in the ocean environment and to characterize its impact on tactical system performance through data analysis, modeling and sensitivity studies. These projects are closely related and some of the data and processing algorithms are shared.

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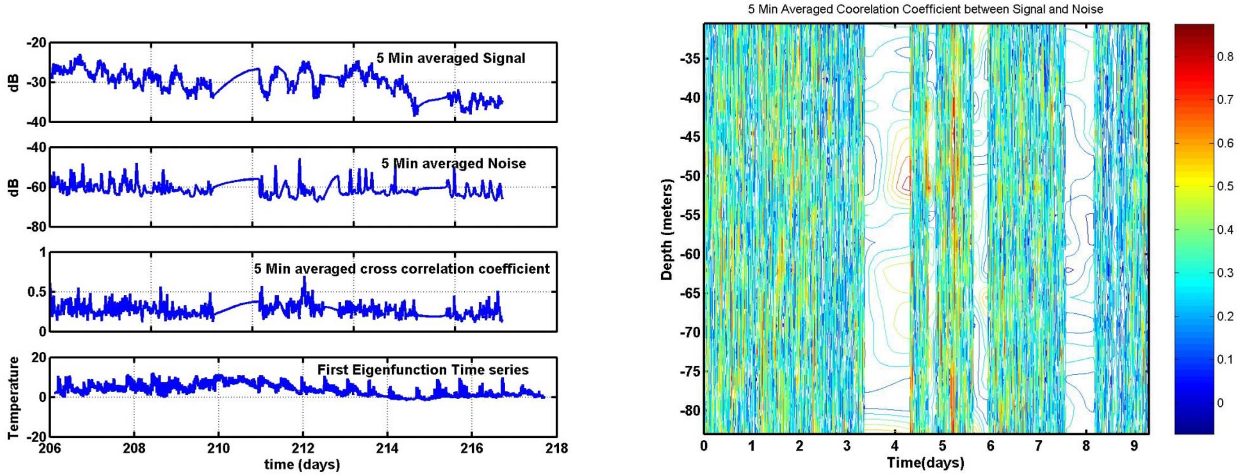
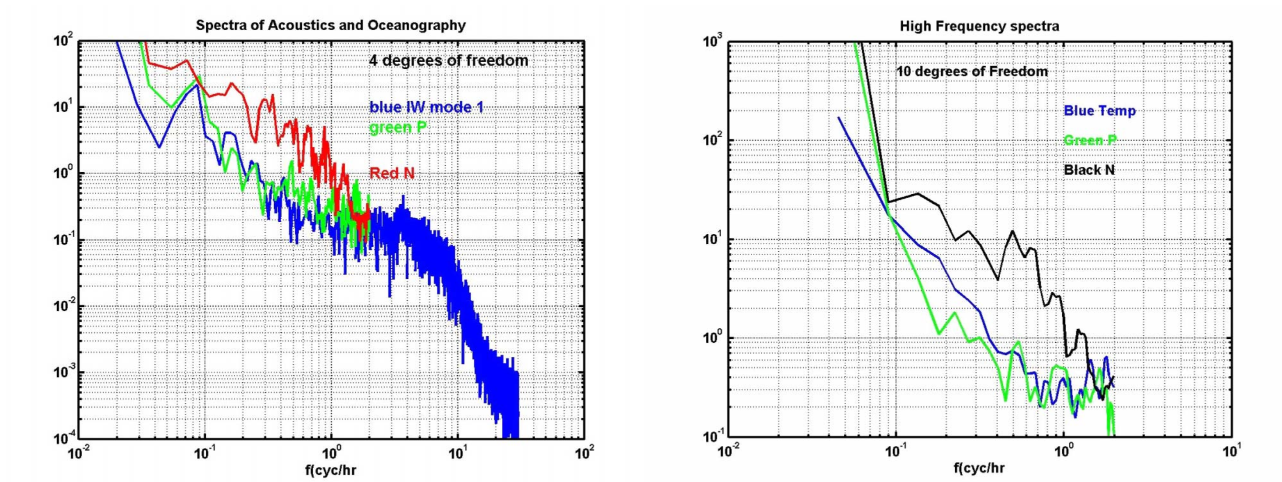


a) b)

Figure 1. a) Depth averaged measurements averaged in 5 minute intervals: signal (top), noise (second), cross correlation coefficient (third), and first mode internal wave time series from the temperature profile (bottom). b) Cross correlation coefficient of signal and noise intensity in 5 minute intervals as a function of depth and time



a) b)

Figure 2. Spectra of depth averaged measurements averaged over 5 minute intervals: signal, noise, and first mode internal wave temperature measurements a) 4 degrees of freedom, b) 10 degrees of freedom.

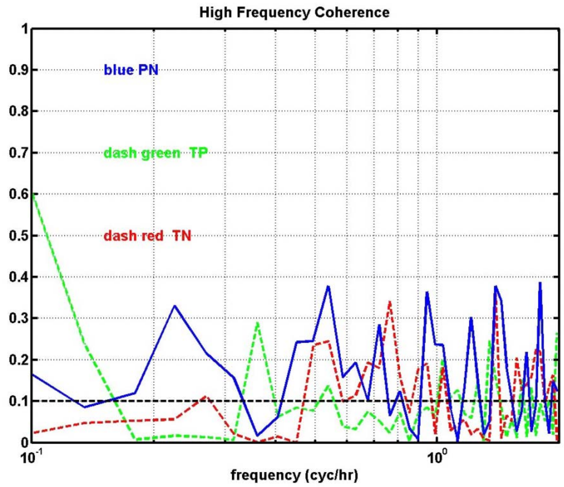


Figure 3. Coherence of depth averaged measurements averaged over 5 minute intervals: signal and noise (blue PN), signal and first mode internal wave temperature (green TP), and noise and first mode internal wave temperature (red TN). The black dashed line at 0.1 is the significance level for this plot with 10 degrees of freedom.